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TRAGEN

Computer Program to Simulate an Aircraft Steered to Follow a Specified Vertical Profile

User's Guide

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May 1983

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TRAGEN

Computer Program to Simulate an Aircraft Steered to Follow a Specified Vertical Profile

User's Guide

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Langley Research Center
under Contract NAS1-15497

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Space Administration

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FOREWORD

The development of this computer program - referred to as TRAGEN - was supported under NASA Contract No. NAS1-15497, by Langley Research Center, Hampton, Virginia. The project Technical Monitors were Samuel A. Morello, Kathy H. Samms, and Robert E. Shanks. At AMA, Inc. the project manager was John A. Sorensen, with engineering support provided by Mark H. Waters. Project programmers were Marianne N. Kidder, Quyen T.L. Nguyen, and Leda C. Patmore.

This Users' Guide describes the program input, program output, and general organization. Appendix A presents the technical material upon which the program is based. Appendix B presents a brief explanation of each of the program subroutines.

I

INTRODUCTION

This document is a technical description and a users' guide for a computer program - called TRAGEN - which is used to simulate an aircraft steered to follow a climbing, cruise, or descending profile or any sequential combination of these flight phases. Specifically, the program simulates the longitudinal dynamics of a medium range twin-jet or tri-jet transport aircraft. For the climbing trajectory, the thrust is constrained to maximum value, and for descent, the thrust is set at idle. For cruise, the aircraft is held in the trim condition.

For climb or descent, the aircraft is steered to follow either (a) a fixed profile which is input to the program or (b) a profile computed at the beginning of that segment of the run. For climb, the aircraft is steered to maintain the given airspeed as a function of altitude. For descent, the aircraft is steered to maintain the given altitude as a function of range-to-go. In both cases, the control variable is angle-of-attack. The given output trajectory is presented and compared with the input trajectory. Step climb is treated just as climb.

For cruise, the Breguet equations are used to compute the fuel burned to achieve a given range and to connect given initial and final values of altitude and Mach number.

TRAGEN is an acronym for trajectory generation. A companion program has been developed which generates optimum profiles which produce input to this program. This companion program - called OPTIM - uses optimization techniques and the energy state method to compute points on the profile. The conditions for climb and descent in OPTIM are consistant with those in TRAGEN. The users' guide for OPTIM appears as a separate document.*

* Anon., "OPTIM-Computer Program to Generate a Vertical Profile which Minimizes Aircraft Fuel Burn or Direct Operating Cost - Users' Guide", NASA CR-166061, March 1983.

The purposes of TRAGEN are three-fold:

1. To verify the accuracy of near-optimum profiles generated by separate programs where simplifying assumptions are used to render the problem tractable. Specifically, TRAGEN can be used to verify the results of OPTIM.

2. To compare the results of flying along a near-optimum profile with those generated by some other means. For example, the aircraft handbook specifies that the aircraft fly along profiles with fixed indicated airspeed and Mach numbers.

3. To use as an evaluation tool for study of possible airborne implementation of autopilot/autothrottle flight management systems. For example, TRAGEN can be used to study the ability of the system to adapt to non-nominal flight conditions (e.g., wind and atmospheric variations, change in destination).

This users' guide is organized as follows:

1) Section II presents, in concise form, the input cards and input data files that must be used to run the program. These are followed by a brief explanation of the options available to the user.

2) Section III presents examples of the program output. This output consists of the profile followed by the aircraft and the reference profile. Without knowing the theory behind the construction of the program, Sections II and III enable the user to make runs and to interpret the results.

3) Section IV presents the program layout in flowchart form.

4) Appendix A gives a technical explanation of the aircraft equations of motion, how the steering control laws are generated, and the Breguet range equation.

5) Appendix B describes the function of TRAGEN's subroutines.

II

INPUT DESCRIPTION

TRAGEN is capable of running a multi-segment mission. Each segment requires up to five input cards and (optionally) two designated data files. The meanings of the variables on the input cards are given first. The program uses Unit 5 as the card input source.

Card 1

This card is the header that appears at the beginning of the segment. The input has an 8A10 format.

Card 2

This card consists of five integer variables used as flags to control the operation of the program, and one real environment variable. The input numbers are right-justified and have a 5I2,F10.0 format. They are:

NSC JTRAJ IAC IWIND IPRT DTEMPK

The meaning of each of these variables is as follows:

NSC — This is the mission segment control variable. The options presently available for NSC are:

- NSC = 2 : climb
- NSC = 3 : cruise
- NSC = 4 : descent
- NSC = 5 : end mission.

This integer is read as the first item of input for each segment, and it is used to route the logic to the correct location within TRAGEN. For the initial segment, weight, airspeed, altitude, and time are all inputs, but they are all transferred within the program to match the end of a given segment with subsequent mission segments.

ITRAJ This flag is used to determine the source of the reference profile to be followed. Values are:

ITRAJ = 1 : Reference trajectory read in from a data file.

ITRAJ = 2 : Reference trajectory computed to follow a sequence of fixed Mach number and indicated airspeed segments.

IAC This flag is used to select which aircraft model to use to generate the desired profile. Current values of IAC are:

IAC = 2 : Medium-range three-engine jet transport aircraft. (nominal model)

IAC = 3 : Medium-range two-engine jet transport aircraft.

IWIND An arbitrary wind profile can be read in on Unit 7. It gives the simulated true wind speed and heading as a function of altitude. Options available for IWIND are:

IWIND = 0 : No wind used.

IWIND = 1 : Constant input wind profile used.

IWIND = 2 : Separate wind profiles are used for climb, cruise and descent.

NOTE: The profile is read only once for each mission (on the first leg), although IWIND may be 0 or 1 for any mission segment.

IPRT This flag is used to obtain additional printout of dynamic variables during the integration process, as described in Section III, Output. Values are:

IPRT = 0 : No extra printout (normal mode).

IPRT = 1 : Reference trajectory printout included.

IPRT = 2 : All printout included.

DTEMPK This is the deviation from standard temperature, in degrees Celsius.

Card 3 (Optional)

This card has 3 real variables with format 3F10.3 and is read only for the initial segment. The variables are:

HO VO WO

The meanings of these variables are as follows:

HO Initial altitude, in ft.

VO Initial indicated airspeed, in kt.

WO Initial aircraft weight, in lb.

<u>Card 4</u>

This card has seven real variables with format 7F10.3. The variables are:

PSIG HF VF CRANGE VIAP1 VIAP2 PMP3

These are defined as

PSIG Aircraft heading over the ground in degrees. PSIG is used with the wind vector to compute the aircraft heading with respect to the air mass, in deg.

HF Final altitude, in ft.

VF Final indicated airspeed, in kt.

CRANGE Cruise only: desired cruise range, mni.

Ignored in cruise if reference trajectory is read in

VIAP1 The desired indicated airspeed in climbing to (or descending from) 10000 ft altitude, in kt.

VIAP2 The desired indicated airspeed in climbing from (or descending to) 10000 ft altitude to (from) intersection with Mach number RMP3.

RMP3 The desired Mach number in climbing from (or descending to) VIAP2 indicated airspeed to (from) intersection with cruise altitude.

required only for descent or initial climb <u>and</u> a reference trajectory is computed.

Card 5 - Climb and Descent only

This card has seven real variables with format 7F10.3. The variables are:

TSTOP DTI RK1 RK2 RK3 RK4 ALFO

The meanings of these variables are:

TSTOP Time from the beginning of the integration to the stop time, in sec.

DTI Integration step size, in sec.

RK1 Proportional gain used to convert airspeed error to angle-of-attack ($\delta\alpha$) command. (°/ft/sec).

RK2 Integral gain used to convert the integral of airspeed error to $\delta\alpha$ command (°/ft).

RK3 Proportional gain used to convert flight path angle error to $\delta\alpha$ command (°/°).

RK4 Integral gain used to convert the integral of flight path angle error to $\delta\alpha$ command (°/° sec).

ALFO The nominal value of angle-of-attack, in deg.

Card 5 - Cruise Segment only. Optional

This card has two real variables with format 3F10.0 and is read only if IWIND $\neq$ 0 and the reference trajectory was not read in. This allows the use of changing winds for multiple cruise segments. The variables are:

VWK PSIW

Here,

VWK Wind speed, in kt,

PSIW Wind source direction, in deg.

Unit 7 - Wind Data (Optional)

This data set is used when IWIND is set to 1 or 2. The input consists of the magnitude of the wind and the direction of its source as a function of altitude. The data format is (3F5.0 I2).

If IWIND = 1, a single wind profile applicable to the entire flight is read in. This profile consists of a set of n cards. Each card has four variables.

HWIND(I) PSIW(I) VW(I) IE

There is one card for each I=1,2,...N, where N is the number of altitudes used for a given wind profile. The meanings of these variables are:

HWIND(I) Beginning (lowest) altitude at which direction PSIW(I) and magnitude VW(I) apply. The program will interpolate for values of PSIW and VW when using altitudes between HWIND(I) and HWIND(I+1).

PSIW(I) Direction of the wind vector source in degrees (i.e., 270° represents a wind from the West).

VW(I) Magnitude of the wind vector, in kt.

IE End-of-wind-table indicator. If IE = 0, the program will expect to read further wind data. If IE = 1, the program assumes that a complete wind table has been read in. Note that when IE = 1, the corresponding altitude should be equal to or greater than any altitude the aircraft is expected to reach.

If IWIND = 2, three wind profiles are read in, one each for climb, cruise, and descent (in that order). Each profile is as described under IWIND = 1. Each profile must end with a non-zero value for IE. If the reference trajectory is computed, the cruise wind is overwritten by data on Card 5.

Unit 11 Input reference data set

These data are read in as the reference variables describing the nominal vertical profile followed by the aircraft during the climb and descent portions of the optimum trajectory. The data are obtained as output from Unit 11 in program OPTIM, although they could be obtained from any other source.

The input consists of up to six binary records of the following form:

Record 1: WORD, NWORD,
WORD may be: CLIMB, CRUISE, or DESCEND.
NWORD is the number of points stored for the specified flight segment.

Record 2: An NWORD by 12 matrix of which only 10 columns are read. For example, for climb, Record 2 contains for JCLIMB = 1,...,NWORD, the following:

CGRAF(JCLIMB,1)	=	E	Specific energy - ft
CGRAF(JCLIMB,2)	=	J	altitude - ft
CGRAF(JCLIMB,3)	=	MACH	Mach
CGRAF(JCLIMB,4)	=	VTASK	true airspeed - kt
CGRAF(JCLIMB,5)	=	GAMMA	flight path angle - deg
CGRAF(JCLIMB,6)	=	FUELUZ	fuel burned - lb
CGRAF(JCLIMB,7)	=	EPR	EPR setting
CGRAF(JCLIMB,8)	=	0	blank
CGRAF(JCLIMB,9)	=	TIME	time
CGRAF(JCLIMB,10)	=	DIST	range traveled - nmi

The same variables are stored in SGRAF for the cruise and DGRAF for the descent portion. The descent profile is generated backwards in time in OPTIM.

III

OUTPUT DESCRIPTION

The output of TRAGEN is compact and generally self explanatory. The output is printed using Unit 6. The input quantity IPRT controls the amount of output.

The first output for each mission segment consists of printing the input. A typical example for a climb segment is shown in Table 1a. An example for a cruise segment is shown in Table 1b. The first line is the header which is used to identify the run. The next several lines print out and explain the run control flags. The last lines print out the real number program control variables. Definitions of these flags and variables are the same as presented in Chapter II.

The cruise segment example also contains the initial and final performance values. The initial values, in this case, have been constructed from the results of the previous climb or cruise segment.

The next set of output is dependent upon whether the reference profiles is read in or computed. If ITRAJ = 2, the profile is computed. If IPRT = 2, printout is included which indicates consecutive variables of this computation. An example of this output is shown as Table 2. The variables that are printed out are:

VIAS	indicated airspeed (ft/sec)
RM	Mach number
D	drag (lb)
TH	thrust (lb)
W	weight (lb)
EDT	energy rate (ft/sec)
FDT	fuel flow rate (lb/hr)
T	time (sec)
R	range (ft)
H	altitude (ft)
V	true airspeed (ft/sec)

```
                    TRAGEN TEST      MATCH OPTIM RUN 600A       READ IN REFERENCE TRAJECTORY
0ITRAJ :  1 REFERENCE TRAJ. READ IN
 IAC   :  3 TWO-JET AIRCRAFT MODEL
0IWIND :  0 NO WIND
 IPRT  :  1 EXTRA PRINT
0DTEMPK:             0.000  DEG TEMPERATURE VARIATION FROM STANDARD
0 NO WIND RUN

0PHASE   STEPS
 CLIMB     85

0PHASE   STEPS
0CRUISE    10

0PHASE   STEPS
0DESCENT   85
0NSC     :  2 CLIMB PHASE


      PROGRAM CONTROL VARIABLES
0        VO(IAS)        WO        HO        TSTOP       DT1        PSIG     VF(IAS)      HF
           KT           LB        FT         SEC        SEC        DEG        KT         FT
0         210.000   100000.        0.        960.        .500     90.000   255.000    33000.
0
0     STEERING VARIABLES
0         RK1        RK2        RK3        RK4        ALFO
0        -.200      0.000      .400       .200       4.600

0
```

Table 1a. Input Data Printout, Climb

```
1NSC     :  3 CRUISE PHASE
0                     CRUISE SEGMENT #1
     IWIND    IPRT     IAC
        1       0       3
OIWIND :  1  INPUT WIND
OIPRT  :  0 NO EXTRA PRINT
OIAC   :  3 TWO-JET AIRCRAFT MODEL
  DESIRED AIRCRAFT HEADING (DEG FROM NORTH)          0.
  WIND SPEED (KT)                                   50.
  WIND DIRECTION (SOURCE HEADING)                    0.

1
            CRUISE SEGMENT PERFORMANCE//      INPUT DATA

          INITIAL CONDITIONS
               ALTITUDE       (FT)     31603.
               MACH NO                  .760
               WEIGHT        (LBS)     92489.
               TIME          (HRS)      .231
               RANGE         (NMI)        88.

          FINAL CONDITIONS
               ALTITUDE       (FT)     32000.
               MACH NO                  .760
               SEGMENT RANGE (NMI)       250.


     OUTPUT DATA

                                     BEGIN       END
          ALTITUDE        (FT)       31603.     32000.
          MACH NO                     .760       .760
          WEIGHT         (LBS)       92489.     89239.
          TIME           (HRS)        .231       .865
          RANGE          (NMI)         88.       338.
          RANGE FACTOR   (NMI)        7899.      7850.
```

Table 1b. Input Data Printout, Cruise

VIAS, RM, D, TH, W, EDT, FDT	421.953	.441	9310.742	23636.067		148877.557	45.760	17210.525	
T, R, H, V, GAM, E, F, EP, VW	216.70	95537.87	9500.00	475.57	5.11	13011.90	1180.01	1.89	0.00
VIAS, RM, D, TH, W, EDT, FDT	421.953	.445	9306.590	23327.584		148819.992	45.138	16993.425	
T, R, H, V, GAM, E, F, EP, VW	228.77	101298.59	10000.00	479.10	5.00	13564.16	1237.70	1.90	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.528	10437.790	22974.488		148762.296	47.966	17542.194	
T, R, H, V, GAM, E, F, EP, VW	261.25	118323.08	10000.00	569.17	0.00	15030.30	1391.03	1.90	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.533	10425.800	22694.833		148608.971	47.331	17330.998	
T, R, H, V, GAM, E, F, EP, VW	273.20	125150.46	10500.00	573.30	4.22	15603.58	1449.27	1.87	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.538	10416.914	22417.644		148550.731	46.651	17122.726	
T, R, H, V, GAM, E, F, EP, VW	285.34	132134.61	11000.00	577.47	4.12	16178.10	1507.70	1.88	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.543	10407.893	22141.652		148492.295	45.964	16916.367	
T, R, H, V, GAM, E, F, EP, VW	297.68	139287.74	11500.00	581.68	4.02	16753.87	1566.41	1.88	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.548	10398.732	21866.892		148433.593	45.269	16711.933	
T, R, H, V, GAM, E, F, EP, VW	310.24	146617.00	12000.00	585.93	3.93	17330.91	1625.40	1.89	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.553	10389.430	21593.398		148374.600	44.568	16509.433	
T, R, H, V, GAM, E, F, EP, VW	323.01	154129.97	12500.00	590.22	3.83	17909.26	1684.71	1.89	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.558	10379.982	21320.850		148315.293	43.858	16308.875	
T, R, H, V, GAM, E, F, EP, VW	336.02	161834.65	13000.00	594.55	3.73	18488.92	1744.35	1.90	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.563	10370.386	21049.372		148255.647	43.141	16110.267	
T, R, H, V, GAM, E, F, EP, VW	349.27	169739.81	13500.00	598.92	3.64	19069.93	1804.37	1.90	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.569	10360.639	20779.186		148195.633	42.416	15913.616	
T, R, H, V, GAM, E, F, EP, VW	362.77	177854.71	14000.00	603.33	3.55	19652.31	1864.78	1.91	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.574	10350.737	20510.327		148135.222	41.684	15718.926	
T, R, H, V, GAM, E, F, EP, VW	376.53	186189.04	14500.00	607.79	3.45	20236.08	1925.62	1.91	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.579	10340.677	20242.826		148074.383	40.945	15526.204	
T, R, H, V, GAM, E, F, EP, VW	390.57	194753.12	15000.00	612.28	3.36	20821.27	1986.92	1.92	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.585	10330.456	19976.717		148013.085	40.199	15335.452	
T, R, H, V, GAM, E, F, EP, VW	404.90	203557.95	15500.00	616.82	3.27	21407.90	2048.71	1.92	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.590	10320.070	19712.029		147951.294	39.447	15146.675	
T, R, H, V, GAM, E, F, EP, VW	419.53	212615.28	16000.00	621.40	3.18	21995.99	2111.03	1.93	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.596	10309.515	19448.793		147888.974	38.687	14959.874	
T, R, H, V, GAM, E, F, EP, VW	434.47	221937.64	16500.00	626.03	3.09	22585.58	2173.91	1.93	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.601	10298.789	19189.328		147826.088	37.931	14773.852	
T, R, H, V, GAM, E, F, EP, VW	449.75	231538.46	17000.00	630.70	3.00	23176.69	2237.40	1.94	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.607	10287.887	18942.418		147762.595	37.216	14587.731	
T, R, H, V, GAM, E, F, EP, VW	465.38	241429.56	17500.00	635.41	2.91	23769.35	2301.52	1.94	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.613	10276.807	18696.704		147698.475	36.494	14403.698	
T, R, H, V, GAM, E, F, EP, VW	481.34	251613.04	18000.00	640.17	2.82	24363.57	2366.22	1.95	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.618	10265.547	18452.216		147633.775	35.765	14221.750	
T, R, H, V, GAM, E, F, EP, VW	497.67	262104.01	18500.00	644.97	2.74	24959.40	2431.55	1.95	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.624	10254.105	18208.983		147568.452	35.029	14041.884	
T, R, H, V, GAM, E, F, EP, VW	514.38	272918.67	19000.00	649.82	2.66	25556.86	2497.54	1.96	0.00
VIAS, RM, D, TH, W, EDT, FDT	506.343	.630	10242.475	17967.034		147502.459	34.286	13864.095	

Table 2. Computed Reference Trajectory Variables.

GAM	flight path angle (deg)
E	specific energy (ft)
F	fuel burned (lb)
EP	EPR setting
VW	wind speed (ft/sec)

These data are useful for checking over the computation of the reference profile.

Next, if IPRT = 1 or 2, the reference profile is printed. This is as computed by the TRAGEN subroutine REFCOM or as read in from Unit 11. An example of an input reference trajectory is shown as Table 3.

Next, the vertical wind profile is printed as shown in Table 4. This is used when there is a non-zero wind, and the flag IWIND is set to 1.

Next, the wind shear data is printed as shown in Table 5. The wind data are taken from Table 4 and used to compute the North and East components of shear every 2000 ft. These shear data are used by the program to compute the real-world (or actual) aircraft longitudinal component of wind as a function of altitude. This simulated actual shear may differ from what is recorded on the reference trajectory data set.

Finally, the main results of the program are printed as shown in Tables 6 and 7. Table 6 shows the first page of printout for a descending profile generated by using the autopilot logic of STEER2 (described later). This print consists of a sequence of two lines of variables shown at nearly equal time points. The first line of variables are those generated by integrating the aircraft equations of motion (described in Appendix A). The second line contains the same variables as obtained from the input nominal reference trajectory. The variables are the same as those printed for the nominal reference trajectory.

This print enables the user to directly compare the performance obtained from the integrated equations of motion with that predicted from another source. (This may be the optimum performance as computed by program OPTIM).

DESCEND OPTIMIZATION REFERENCE TRAJECTORY DATA

TIME SEC	RANGE FT	ALTITUDE FT	AIRSPEED FT/S	GAMMA DEG	ENERGY FT	FUEL LB	EPR	WIND V FT/S
-874.646	-464602.110	33118.838	736.845	-3.254	41538.163	0.000	1.803	-54.834
-869.555	-461141.260	32922.101	735.246	-3.890	41339.163	1.782	1.803	-55.911
-864.487	-457706.497	32688.562	735.626	-4.075	41089.163	3.555	1.803	-57.171
-859.439	-454294.311	32445.442	735.225	-4.105	40839.163	5.323	1.803	-58.462
-854.416	-450907.939	32202.402	734.920	-7.441	40589.163	7.080	1.803	-59.727
-849.420	-447547.153	31763.484	743.151	-3.940	40339.163	8.829	1.803	-61.556
-844.599	-444273.049	31538.009	742.088	-4.129	40089.163	10.517	1.803	-62.308
-839.791	-441016.888	31302.962	741.439	-4.135	39839.163	12.199	1.803	-63.085
-835.005	-437781.890	31069.108	740.737	-4.205	39589.163	13.874	1.803	-63.851
-830.238	-434567.497	30832.790	740.042	-5.638	39339.163	15.543	1.803	-64.617
-825.494	-431373.696	30523.103	742.734	-6.581	39089.163	17.203	1.803	-65.610
-820.827	-428225.585	30159.913	747.625	-6.724	38839.163	18.837	1.803	-66.757
-816.276	-425138.800	29795.970	752.517	-8.714	38589.163	20.430	1.803	-67.427
-811.838	-422138.356	29336.073	750.799	-4.468	38089.163	21.983	1.803	-67.814
-803.026	-416145.977	28867.847	749.435	-4.517	37589.163	25.067	1.803	-68.207
-794.290	-410220.636	28399.775	748.062	-3.908	37089.163	28.125	1.803	-68.601
-785.629	-404369.597	28000.061	743.733	-3.755	36589.163	31.156	1.803	-68.937
-776.945	-398546.009	27617.815	738.617	-4.339	36089.163	34.195	1.803	-69.258
-768.212	-392729.897	27176.469	736.055	-5.780	35589.163	37.273	1.803	-69.629
-759.515	-386949.473	26591.354	739.769	-6.178	35089.163	40.358	1.803	-70.121
-751.063	-381304.954	25980.321	744.587	-6.360	34589.163	43.387	1.803	-70.668
-742.889	-375816.467	25368.546	749.405	-6.555	34089.163	46.353	1.803	-72.211
-734.984	-370485.589	24756.029	754.224	-6.748	33589.163	49.261	1.803	-73.756
-727.333	-365302.812	24142.770	759.044	-6.915	33089.163	52.142	1.803	-75.302
-719.915	-360240.038	23528.767	763.865	-4.929	32589.163	55.039	1.803	-72.493
-712.727	-355289.522	23101.833	760.779	-4.979	32089.163	57.947	1.803	-69.622
-705.543	-350343.117	22670.937	757.848	-4.981	31589.163	60.904	1.803	-66.724
-698.367	-345402.738	22240.346	754.893	-2.817	31089.163	63.910	1.803	-63.828
-691.199	-340488.764	21998.583	743.797	-3.054	30589.163	66.965	1.803	-62.206
-683.801	-335487.522	21731.725	733.634	-5.081	30089.163	70.119	1.803	-61.242
-676.192	-330392.263	21269.698	731.966	-5.162	29589.163	73.368	1.803	-59.559
-668.627	-325326.787	20812.099	730.098	-5.234	29089.163	76.655	1.803	-57.875
-661.100	-320287.616	20350.470	728.404	-4.593	28589.163	79.980	1.803	-56.161
-653.615	-315282.869	19948.393	724.062	-5.682	28089.163	83.343	1.803	-54.722
-646.092	-310267.783	19449.400	724.017	-5.742	27589.163	86.763	1.803	-53.417
-638.663	-305305.758	18950.413	723.972	-5.706	27089.163	90.219	1.803	-52.028
-631.326	-300396.444	18459.881	723.651	-5.368	26589.163	93.710	1.803	-50.585

Table 3. The Input or Computed Reference Trajectory

WIND DATA

ALT(FT),	VW(KNOTS),	VW(FT/SEC),	PSIW(DEG)
0.	0.00	0.00	205.
2000.	4.00	6.75	205.
4000.	9.00	15.19	205.
6000.	14.00	23.63	205.
8000.	13.00	21.94	240.
10000.	14.00	23.63	275.
12000.	23.00	38.82	285.
14000.	22.00	37.13	275.
16000.	27.00	45.57	270.
18000.	31.00	52.32	290.
20000.	33.00	55.70	280.
22000.	37.00	62.45	275.
24000.	45.00	75.95	275.
26000.	42.00	70.89	275.
28000.	41.00	69.20	275.
30000.	40.00	67.51	275.
32000.	36.00	60.76	270.
34000.	30.00	50.63	280.
36000.	28.00	47.26	300.
38000.	31.00	52.32	310.
40000.	31.00	52.32	310.
42000.	31.00	52.32	310.
44000.	31.00	52.32	310.
46000.	31.00	52.32	310.

Table 4. Vertical Wind Profile

WIND SHEAR DATA

ALT	VW	PSIW	D(WX)/DH	D(WY)/DH
0.	0.00	205.	-.003059	-.001427
2000.	6.75	205.	-.003824	-.001783
4000.	15.19	205.	-.003824	-.001783
6000.	23.63	205.	.005222	-.004508
8000.	21.94	240.	.006515	-.002269
10000.	23.63	275.	.003994	-.006979
12000.	38.82	285.	-.003406	.000253
14000.	37.13	275.	-.001618	-.004290
16000.	45.57	270.	.008948	-.001798
18000.	52.32	290.	-.004112	-.002842
20000.	55.70	280.	-.002115	-.003680
22000.	62.45	275.	.000588	-.006726
24000.	75.95	275.	-.000221	.002522
26000.	70.89	275.	-.000074	.000841
28000.	69.20	275.	-.000074	.000841
30000.	67.51	275.	-.002942	.003247
32000.	60.76	270.	.004396	.005448
34000.	50.63	280.	.007418	.004469
36000.	47.26	300.	.005001	.000423
38000.	52.32	310.	0.000000	0.000000
40000.	52.32	310.	0.000000	0.000000
42000.	52.32	310.	0.000000	0.000000
44000.	52.32	310.	0.000000	0.000000

Table 5. Wind Shear Data as Functions of Altitude

1 CLIMB TRAJECTORY COMPARISON USING CONTROL OPTION 1

0	TIME SEC	RANGE NMI	ALTITUDE FT	AIRSPEED FT/S	AIRSPEED KT	GAMMA DEG	ENERGY FT	FUEL LB	EPR	WIND FT/S	MACH NO	ALPHA DEG
0ACT	0.000	0.000	5.0	354.440	210.000	0 000	1950.7	0.000	1.849	0.000	.317	4.600
REF	0.000	0.000	0.0	354.440	210.000	0.000	1950.7	0.000	1.849	0.000	.317	
0ACT	8.500	.527	-8.9	397.992	235.804	.975	2452.7	35.817	1.840	0.000	.356	4.669
REF	8.203	410	2.9	397.042	235.241	054	2450.7	34.730	1.840	0.000	.356	
0ACT	18.500	1.209	192.1	430.243	254.912	3 335	3068.7	78.269	1.835	0.000	.386	3.962
REF	16.145	.944	188.6	421.763	249.888	3.274	2950.7	68.409	1.837	0.000	.378	
0ACT	28.500	1.924	677.9	440.101	260.752	8.355	3688.0	120.631	1.838	0.000	.395	3.857
REF	24.181	1.499	672.0	423.026	250.636	8.188	3450.7	102.079	1.842	0.000	.380	
0ACT	35 500	2.427	1091.8	442.751	262.323	6.749	4138.2	149.937	1.842	0.000	.398	3.394
REF	32.255	2.059	1098.5	428.586	253.930	7 126	3950.7	135.585	1.846	0.000	.385	
0ACT	44.000	3.044	1572.7	446.398	264.484	7.757	4669.5	185.171	1.847	0.000	.402	3 485
REF	40.409	2.631	1563.7	431.194	255.475	7.626	4450.7	169.042	1.851	0.000	.388	
0ACT	51.500	3.591	2011.3	448.596	265.786	7.344	5138 6	215.901	1.852	0.000	.405	3.523
REF	48.638	3.211	2025.4	434.039	257.161	7.453	4950.7	202.440	1.856	0.000	.391	
0ACT	59.500	4.178	2471.0	451.051	267.241	7.294	5632.7	248.329	1.858	0.000	.407	3.516
REF	56.935	3.801	2486.9	436.891	258.851	7.337	5450.7	235.775	1.862	0.000	.395	
0ACT	68.000	4.805	2954.3	453.681	268.799	7.163	6153.0	282.421	1.864	0.000	.411	3.538
REF	65.303	4.399	2947.7	439.766	260.554	7.218	5950 7	269.052	1.868	0.000	.398	
0ACT	76.000	5.399	3404.6	456.157	270.265	7.049	6638.2	314.176	1.870	0.000	.413	3.550
REF	73.743	5.007	3408.0	442.663	262.271	7.100	6450.7	302.274	1.874	0.000	.401	
0ACT	84.500	6.034	3877.8	458.801	271.832	6.931	7149.0	347.568	1.876	0.000	.417	3.563
REF	82.257	5.624	3867.8	445.583	264.001	6.983	6950.7	335.445	1.880	0.000	.405	

Table 6. Actual and Reference Optimum Descent Profiles

Table 7 shows the first page of a more dense printout for a climb profile, obtained by setting the flag IPRT = 2. The print contains the same two lines of variables as shown in Table 6 at various reference points in time. It also shows three different types of secondary printout between these reference points. From Table 7, these are:

Type 1: DGDH DVDH GC1 VC1 DT ICFL

These are variables generated by the command logic (STEER1) to produce steering commands over the next period of time. For the climb profile governed by STEER1, these variables are:

DGDH the gradient of flight path angle with altitude (deg/ft),

DVDH the gradient of airspeed with altitude (ft/sec/ft),

GC1 constant term in the flight path-angle command (deg)

VC1 constant term in the airspeed command (ft/sec),

DT time interval over which the command applies (sec),

ICFL flag used to command (a) airspeed and flight path angle (ICFL = 1), or (b) only flight path angle (ICFL = 2).

Type 2: VCM GCM DVD DGD DALF ALF VEI GEI

These variables are generated four times per integration step. Their meanings are:

VCM commanded airspeed (ft/sec),

GCM commanded flight path angle (deg),

DVD error in airspeed (deg),

DGD error in flight path angle (deg),

DALF commanded incremental angle-of-attack $\delta\alpha$ (deg),

ALF total commanded angle-of-attack (deg),

VEI integral of airspeed error (ft),

GEI integral of flight-path-angle error (deg-sec).

```
 CLIMB TRAJECTORY COMPARISON USING CONTROL OPTION   1
       TIME         RANGE      ALTITUDE      AIRSPEED        GAMMA      ENERGY         FUEL          EPR         WIND V         ALPHA
       SEC           FT          FT           FT/S            DEG         FT            LB                         FT/S           DEG

ACT         0.000        0.000        5.000        350.154        0.000      1903.843       0.000        1.850        0.000    4.000
REF         0.000        0.000        0.000        350.154        0.000      1903.843       0.000        1.850        0.000
 DGDH,DVDH,GC1,VC1,DT,ICFL          0.0000       10.4956          0.0000        387.5684        100.0000    2
 VCM, GCM, DVD, DGD, DALF, ALF, VEI, GEI       0.00       0.00       0.00       0.00      0.00      4.00       0.00       0.00
 L,W,TH,D,MAS,GAM,ALF    69266.1    95000.0   21555.5    4201.2     2952.7       0.0        .1
 HDD,VAD,XD,HDT,HD,VA,X,H      -8.2       5.9     350.2       0.0       0.0      350.2       0.0       5.0
 VCM, GCM, DVD, DGD, DALF, ALF, VEI, GEI       0.00       0.00       0.00        .20       .08      4.08       0.00       0.00
 L,W,TH,D,MAS,GAM,ALF    70763.9    94999.4   21548.9    4269.5     2952.7       -.0        .1
 HDD,VAD,XD,HDT,HD,VA,X,H      -7.7       5.9     351.0      -1.2      -1.2      351.0      52.5       5.0
 VCM, GCM, DVD, DGD, DALF, ALF, VEI, GEI       0.00       0.00       0.00        .44       .21      4.21       0.00        .14
 L,W,TH,D,MAS,GAM,ALF    73122.0    94998.4   21539.1    4378.6     2952.6       -.0        .1
 HDD,VAD,XD,HDT,HD,VA,X,H      -6.9       6.0     352.4      -2.7      -2.7      352.4     131.9       4.1
 VCM, GCM, DVD, DGD, DALF, ALF, VEI, GEI       0.00       0.00       0.00        .66       .26      4.26       0.00       -.04
 L,W,TH,D,MAS,GAM,ALF    74126.6    94997.9   21533.5    4426.3     2952.6       -.0        .1
 HDD,VAD,XD,HDT,HD,VA,X,H      -6.6       6.1     353.0      -4.1      -4.1      353.1     175.1       5.2
M, A, EP, TH, GA, L,D              .3162       4.2562       1.8494    21533.5410       -.6609   74126.6269     4426.2809
AZ, AX, VX, VZ, WD, V, X, H       -6.5957       6.0673     353.0401      -4.0725      -4.2034     353.1304     175.8139          4.044

 VCM, GCM, DVD, DGD, DALF, ALF, VEI, GEI       0.00       0.00       0.00        .60       .27      4.27       0.00        .16
 L,W,TH,D,MAS,GAM,ALF    74358.5    94997.9   21533.7    4436.8     2952.6       -.0        .1
 HDD,VAD,XD,HDT,HD,VA,X,H      -6.5       6.0     353.1      -3.7      -3.7      353.1     175.8       4.0
 VCM, GCM, DVD, DGD, DALF, ALF, VEI, GEI       0.00       0.00       0.00        .75       .35      4.35       0.00        .25
 L,W,TH,D,MAS,GAM,ALF    75911.3    94997.3   21527.2    4510.5     2952.6       -.0        .1
 HDD,VAD,XD,HDT,HD,VA,X,H      -6.0       6.1     354.0      -4.7      -4.7      354.0     228.8       3.5
 VCM, GCM, DVD, DGD, DALF, ALF, VEI, GEI       0.00       0.00       0.00        .93       .47      4.47       0.00        .49
 L,W,TH,D,MAS,GAM,ALF    78245.6    94996.3   21517.6    4623.0     2952.6       -.0        .1
 HDD,VAD,XD,HDT,HD,VA,X,H      -5.2       6.1     355.4      -5.8      -5.8      355.4     308.9       2.0
 VCM, GCM, DVD, DGD, DALF, ALF, VEI, GEI       0.00       0.00       0.00       1.12       .53      4.53       0.00        .41
 L,W,TH,D,MAS,GAM,ALF    79427.5    94995.8   21512.2    4680.7     2952.6       -.0        .1
 HDD,VAD,XD,HDT,HD,VA,X,H      -4.8       6.2     356.1      -6.9      -6.9      356.1     352.4       2.5
M, A, EP, TH, GA, L,D              .3190       4.5285       1.8488    21512.1759      -1.1151   79427.5039     4680.7179
AZ, AX, VX, VZ, WD, V, X, H       -4.8132       6.1717     356.0615      -6.9309      -4.2069     356.1770     353.1193          1.462

 VCM, GCM, DVD, DGD, DALF, ALF, VEI, GEI       0.00       0.00       0.00       1.05       .53      4.53       0.00        .57
 L,W,TH,D,MAS,GAM,ALF    79516.2    94995.8   21512.3    4685.1     2952.6       -.0        .1
 HDD,VAD,XD,HDT,HD,VA,X,H      -4.8       6.1     356.1      -6.5      -6.5      356.2     353.1       1.5
 VCM, GCM, DVD, DGD, DALF, ALF, VEI, GEI       0.00       0.00       0.00       1.16       .61      4.61       0.00        .73
 L,W,TH,D,MAS,GAM,ALF    81055.6    94995.2   21506.0    4761.0     2952.5       -.0        .1
 HDD,VAD,XD,HDT,HD,VA,X,H      -4.3       6.2     357.0      -7.2      -7.2      357.1     406.5        .5
 VCM, GCM, DVD, DGD, DALF, ALF, VEI, GEI       0.00       0.00       0.00       1.27       .72      4.72       0.00       1.04
 L,W,TH,D,MAS,GAM,ALF    83271.4    94994.2   21496.0    4872.2     2952.5       -.0        .1
 HDD,VAD,XD,HDT,HD,VA,X,H      -3.5       6.2     358.4      -7.9      -7.9      358.5     487.3      -1.5
 VCM, GCM, DVD, DGD, DALF, ALF, VEI, GEI       0.00       0.00       0.00       1.42       .78      4.78       0.00       1.05
 L,W,TH,D,MAS,GAM,ALF    84563.6    94993.7   21490.6    4937.3     2952.5       -.0        .1
 HDD,VAD,XD,HDT,HD,VA,X,H      -3.1       6.2     359.1      -8.9      -8.9      359.2     531.2      -1.5
M, A, EP, TH, GA, L,D              .3218       4.7793       1.8481    21490.6126      -1.4210   84563.6122     4937.2793
AZ, AX, VX, VZ, WD, V, X, H       -3.0736       6.2089     359.1187      -8.9086      -4.2105     359.2590     531.9374         -2.314

 VCM, GCM, DVD, DGD, DALF, ALF, VEI, GEI       0.00       0.00       0.00       1.35       .78      4.78       0.00       1.18
```

Table 7. Climb Profile With Secondary Printout

Type 3: M A EP TH GA L D
AZ AX VX VZ WD V X H

These variables indicate the state of the aircraft at the end of each integration step. The meanings of these variables are:

M Mach number,

A angle-of-attack (deg),

EP EPR setting,

TH thrust (lb),

GA flight path angle (deg),

L lift (lb),

D drag (lb),

AZ vertical acceleration (ft/sec^2),

AX horizontal acceleration (ft/sec^2),

VX ground speed (ft/sec),

VZ altitude rate (ft/sec),

WD fuel burn rate (lb/sec),

V airspeed (ft/sec),

X distance-to-go or range (ft),

H altitude (ft).

If IPRT = 2, secondary output is also created for the descent trajectory. Again, there are three types of secondary printout. These are:

Type 1: HP H RP X DHDX GC1 DT

These are variables used and generated by the command logic (STEER2) to produce steering commands over the next period of time. For the descent profile governed by STEER2, these variables are:

HP the next reference altitude point (ft),

H current measured altitude (ft),

RP the next reference range point (ft),

X current measured range (ft),

DHDX computed gradient of dh/dx,

GC1 commanded inertial flight path angle (deg),

DT time interval over which the command applies (sec). In this case, the command GCL is regenerated when X becomes greater than RP.

Type 2: GCM GMG DALF ALF GEI

These variables are generated four times per integration step. They are the result of a fourth-order Runge-Kutta-Gill integration method which is subroutine GO. The meanings of these variables are:

GCM commanded inertial flight path angle (deg),

GMG actual inertial flight path angle (deg),

DALF commanded incremental angle-of-attack $\delta\alpha$ (deg),

ALF total commanded angle-of-attack ($\alpha_o + \delta\alpha$) (deg),

GEI integral of flight-path-angle error (deg-sec).

Type 3 is the same format as produced for climb.

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IV

PROGRAM ORGANIZATION AND SUBROUTINES

This section gives a brief overview of the process used in TRAGEN to generate steering commands and to integrate the equations of motion for an aircraft following a given reference trajectory. This section also contains a brief description of each of TRAGEN's thirty-nine subroutines. The technical details upon which the program is based are presented in Appendix A. A more detailed description of the subroutines is presented in Appendix B.

Figure 1 is a flow chart of the steps followed by TRAGEN to simulate an aircraft steered to follow an input or computed reference profile. The steps followed by the program are as follows:

1. Read in the control flags, reference trajectory, prevailing wind model, and program control parameters. Use these data to initialize the program variables.

2. If the desired segment is a cruise, calculate the cruise performance. Then return to step 1.

3. If mission segment is a climb, and not the initial segment, perform a step climb subsegment.

4. If a reference trajectory is to be computed (ITRAJ equals 2), compute a reference climb or descent trajectory. This consists of incrementing the altitude in steps of 500 ft, and computing the associated aircraft variables so that the desired true airspeed is maintained. The desired true airspeed is computed from the input sequence of indicated airspeeds VIAP1 and VIAP2 and the Mach number RM3. This speed profile is similar to those specified in a typical pilot's handbook.

5. Start the simulation update process. This consists of first writing the state variables as determined from integrating the aircraft equations of motion. These are written along with similar variables taken from the input reference profile. The

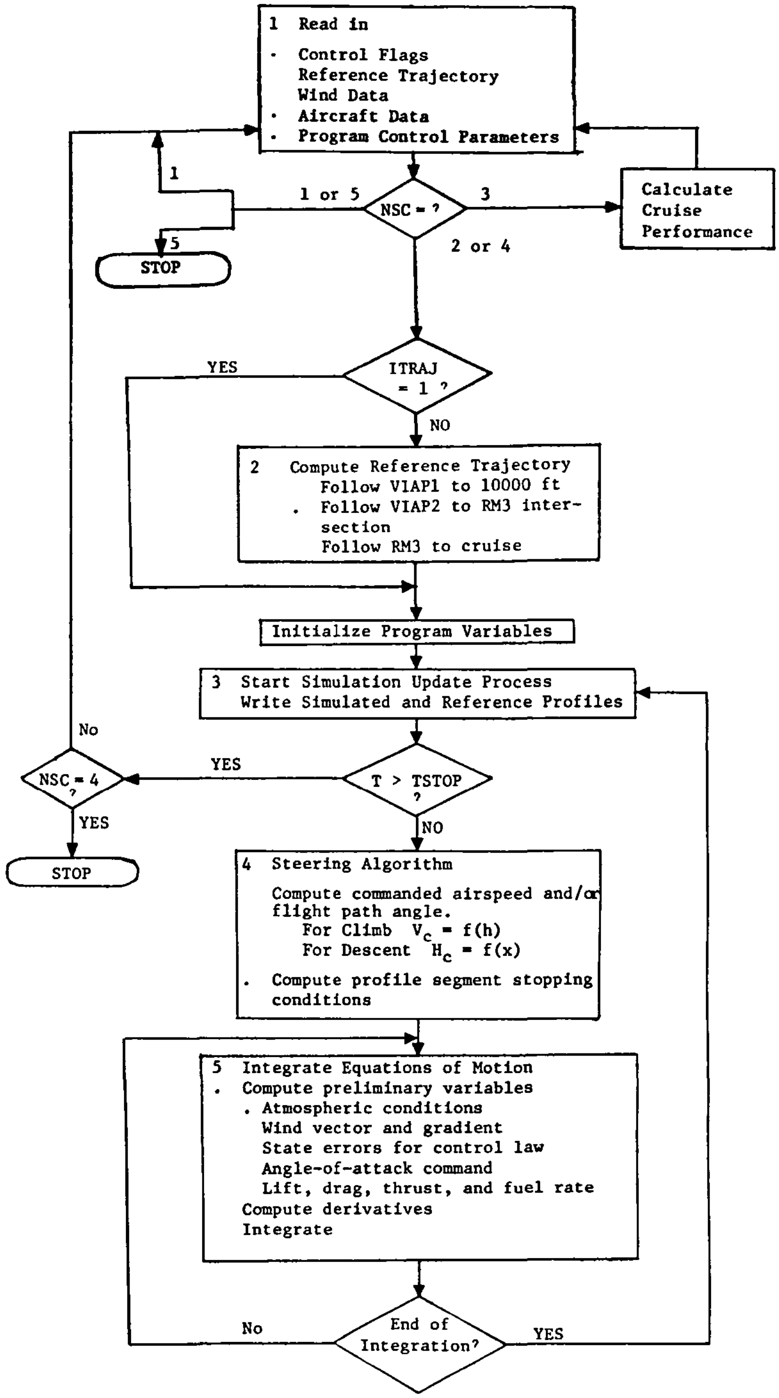

Figure 1. Macro Flow Chart Trajectory Generation Program

reference profile consists of a sequence of discrete points where the specific energy or the altitude changes in steps of 500 ft. The steering algorithm commands a continuous trajectory which connects these points. After the actual and reference trajectory states are written, the program determines whether the stopping time (TSTOP) has been reached.

6. If the simulation is to continue, the program next calls the appropriate steering algorithm. One method is available to generate angle-of-attack commands to maintain airspeed as a function of altitude for the climb profile. A different method is available to generate angle-of-attack commands to maintain altitude and flight path angle as a function of range-to-go for the descent profile. This block is called when the aircraft is near each reference point along the input profile.

7. This step integrates the equations of motion of the aircraft. The equation derivatives are computed four times per Runge Kutta integration step (Input DTI). Integration continues until the simulated aircraft reaches the next reference value of altitude or airspeed during climb or the next reference value of range during descent. At the end of the segment (next reference point reached), the program loops back to Step 3.

8. Return to step 1.

These steps are explained in more detail in Appendix A.

TRAGEN is programmed in FORTRAN, and it consists of the main executive program and thirty-nine subroutines and functions. These thirty-nine subroutines are called to execute the steps depicted in Fig. 1. Explanations of the program and its subroutines are presented in Appendix B.

The program subroutines can be grouped into four categories:

1. models of airborne software used to compute and generate steering commands,

2. aerodynamic, propulsion, and flight dynamics models,

3. flight condition models, and

4. utility programs.

Under Category 1, the subroutines are:

ACRUSE Sets up program variables to initialize cruise segment.

CMACTL Initializes variables and controls computational flow for integrated climb and descent segments.

CREWZ Computes a cruise flight path given the initial and final altitude and Mach number, initial weight, and desired range.

REFCOM Computes a reference flight path that follows an indicated airspeed (VIAP1) from sea level to 10000 ft, an indicated airspeed (VIAP2) from 10000 ft to intersection with Mach number (RM3), and RM3 up to cruise altitude;

SETREF Sets up reference trajectory, either computed or read in.

STEER1 Computes coefficients for a continuous angle-of-attack perturbation command control law that maintains airspeed as a function of altitude. This is a closed-loop command algorithm for climb;

STEER2 Computes coefficients for a continuous angle-of-attack perturbation command control law that maintains altitude as a function of range-to-go. This is a closed-loop command algorithm for descent;

VTCM Computes true airspeed, energy, energy rate, and fuel rate from indicated airspeed (or Mach number), altitude, and weight;

Under Category 2, the routines are:

DATTRI	Block data containing engine data for the tri-jet turbofan engine.
DATTWN	Block data containing engine data for the twin-jet aircraft.
CDRAG	Calls appropriate routine to compute the drag coefficient.
CDRAG2	Computes the drag coefficient for the tri-jet aircraft.
CDRAG3	Computes the drag coefficient for the twin-jet aircraft.
CLIFTT	Calls appropriate routine to compute the lift coefficient.
CLIFT2	Computes the lift coefficient as a function of Mach number, altitude, and angle-of-attack for the tri-jet aircraft.
CLIFT3	Computes the lift coefficient for the twin-jet aircraft.
ENGEPR	Calls appropriate routine to compute engine thrust and fuel flow rate.
ENGEP2	Computes the engine thrust and fuel flow rate as functions of altitude, Mach number, temperature variations, and EPR setting for the tri-jet aircraft.
ENGEP3	Computes the engine thrust and fuel flow rate for the twin-jet aircraft.
ENGIDL	Computes the engine thrust and fuel flow rate as functions of altitude and Mach number when EPR has been set at idle.
FSUB	Computes the derivative values of the first order differential equations representing the longitudinal dynamics and fuel burn of the twin-jet aircraft.
TRIM	Computes the thrust and angle-of-attack for maintaining constant speed levels for a given altitude and cruise weight.

Under Category 3, the subroutines are:

ATLOW	Generates atmospheric density, pressure, temperature, and speed-of-sound as functions of altitude.
WIND	Computes the wind vector and its effect along the ground track of the aircraft.
WIND1	Computes the longitudinal wind gradient as a function of altitude.
WINDIN	Reads in the data and sets up the wind profile as a function of altitude.
WINDSH	Computes wind gradient components as functions of altitude.

Under Category 4, the subroutines are:

DBLSRC	Performs a linear double table look-up.
FIAS	Converts indicated airspeed in feet/second to Mach number.
FIASM	Converts Mach number to indicated airspeed in knots.
GO	The fourth-order Runge-Kutta-Gill numerical integration subroutines.
OSUB	Called by GO for special printout and to stop the integration process when a variable reaches a certain magnitude.
PAGE	Starts a new page of printout.
POLYE1	Evaluates a polynomial for some fixed value of the independent variable.
POLY2	Evaluates a polynomial function of two independent variables.
SERCHI	Searches for a point in a monotonically increasing array.
SGLSRC	Performs a linear table look-up.
TRACIT	Traces subroutine calling sequence in case of program error.

The interrelationship between these subroutines is also presented in Appendix B.

APPENDIX A

AIRCRAFT EQUATIONS OF MOTION AND AUTOPILOT MODELS

The objective of the TRAGEN program is to simulate an aircraft being steered to fly along an input or computed reference trajectory. This trajectory may be any combination of climb, cruise, and descent profiles. This simulation must be accurate enough such that the performance of the aircraft (in terms of fuel burned and time required to reach the destination point) is adequately determined, as measured from the output.

The purpose of this appendix is to provide the analytical expressions upon which the simulation was developed; this is done in three parts. The first section below defines the overall system and presents the differential equations of motion and fuel burn. The second section describes different methods for generating typical guidance commands and autopilot equations used for climb and descent. The third section derives the Breguet equation used for cruise segment calculations.

Equations of Motion and Fuel Burn

To examine the vertical profile of the aircraft (i.e., altitude and airspeed vs range), the longitudinal equations of motion are of primary importance. The control variables in this longitudinal plane are the angle-of-attack α and the magnitude of the thrust vector T. These quantities are shown with respect to aircraft airspeed V_a, lift L, drag D, weight W, and flight path angle γ in Fig. A.1.

The kinematic equations of motion of the aircraft in the longitudinal plane are

$$\begin{aligned} \dot{x} &= V_g \\ \dot{h} &= V_a \sin\gamma \,, \end{aligned} \qquad \text{(A.1)}$$

where

x = distance, or range, measured on the ground,

h = altitude,

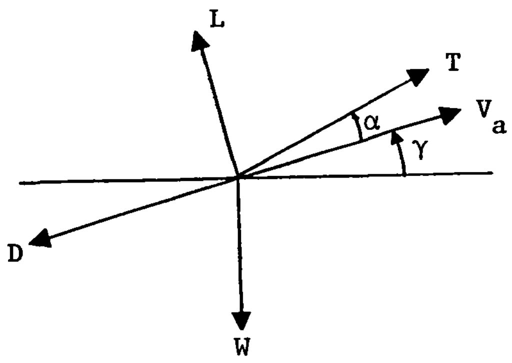

Figure A.1 Vector Diagram of Longitudinal Forces

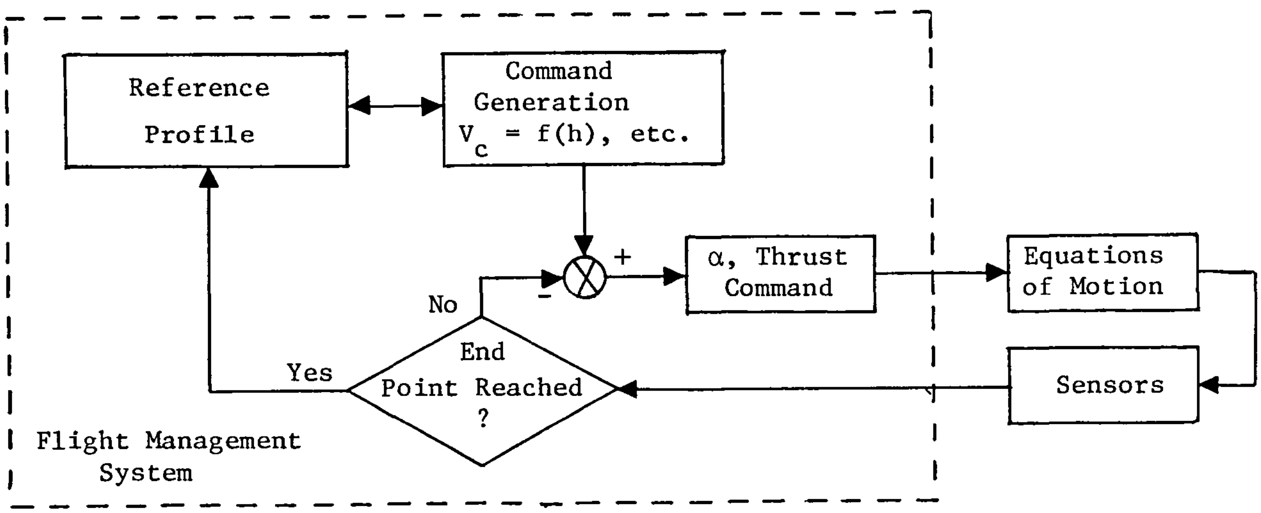

Figure A.2. Elements of the Longitudinal Aircraft System

V_g = ground speed (magnitude of $\overline{V}_g = \overline{V}_w + \overline{V}_a \cos\gamma$),

V_w = wind speed.

The inertial speed along the airspeed vector $\overline{V}_a$ is

$$V_I = V_a + V_w \cos\gamma \cos\delta , \tag{A.2}$$

where δ is the angle between the horizontal projection of $\overline{V}_a$ and $\overline{V}_w$. From Fig. A.1, the time rate of change of this vector for constant γ is

$$\dot{V}_I = \dot{V}_a + \dot{V}_w \cos\gamma \cos\delta = \frac{1}{m}(T \cos\alpha - D - W \sin\gamma). \tag{A.3}$$

The time rate of change of the wind speed is

$$\begin{aligned} \dot{V}_w &= \frac{\partial V_w}{\partial h}\dot{h}, \\ &= \frac{\partial V_w}{\partial h} V_a \sin\gamma . \end{aligned} \tag{A.4}$$

By substituting Eq. (A.4) into Eq. (A.3) and solving for V_a, one obtains

$$\dot{V}_a = \frac{1}{m}(T \cos\alpha - D - W \sin\gamma) - \frac{\partial V_w}{\partial h} V_a \sin\gamma \cos\gamma \cos\delta. \tag{A.5}$$

This ignores the time rate of change of the wind direction. From Fig. A.1, one can write

$$\ddot{h} = \frac{1}{m}(L \cos\gamma - W + T \sin(\gamma + \alpha) - D \sin\gamma). \tag{A.6}$$

Equations (A.5) and (A.6) represent the kinetic equations of motion of the aircraft.

The remaining term that must be accounted for is the time-varying weight of the aircraft. Specifying the thrust also specifies the fuel burn rate $\dot{f}$. Thus, the weight changes at the rate

$$\dot{W} = -\dot{f} . \tag{A.7}$$

Equations (A.1), (A.5), (A.6), and (A.7) are the five basic equations used to represent the longitudinal dynamics of the aircraft.

Further refinement could be added to these equations to include the effects of the following:

1). throttle dynamics (including transient fuel flow rates);

2). relationship between throttle position, EPR setting, and thrust;

3). short period dynamics relating time rate of change of angle-of-attack, pitch rate, and pitch angle to elevator deflection;

4). required turning (lateral) motion for flying over fixed waypoints; and

5). variable wind direction and gust effects.

However, these effects are considered to be of second order, and not required for the intent of this simulation. For a more exact autopilot simulation, they would be required.

The flight path angle is defined as

$$\gamma = \sin^{-1} (\dot{h}/V_a) \tag{A.8}$$

By differentating this expression and using Eqs (A.5) and (A.6), one obtains

$$\dot{\gamma} = \frac{1}{mV_a} (T \sin \alpha - W \cos \gamma + L + \frac{\partial V_w}{\partial h} V_a \sin^2 \gamma \cos \delta). \tag{A.9}$$

Equation (A.9) can be used in place of Eq. (A.6).

Steering Procedures

The climb and descent reference trajectories which are given to be followed consist of a sequence of points containing values of time, range, altitude, airspeed, flight path angle, specific energy, weight, and other variables. Any of these quantities which is measureable and monotonically changing can serve as the independent variable. To minimize airborne computer memory requirements, it is important to make the stored data representing the reference trajectory as compact as possible.

In this study, a set of steering equations are used to take points from the reference trajectory, convert these points to reference trajectory

commands, and then use these commands to set values of the control variables. This steering process represents a rudimentary form of an autopilot.

The steering process consists of commanding the thrust T and angle-of-attack α values so that the aircraft follows the reference as closely as possible. The system that includes this process is depicted by the block diagram in Fig. A.2. Note that flying along a reference trajectory consists of steering to connect a series of reference points. When a reference point is reached, new steering commands must be issued so that the aircraft will then be guided to the next reference point.

To fly along the reference path, an independent variable is first chosen. For this study, two different independent variables were chosen - range and altitude. Then, the remaining variables - primarily airspeed, flight path angle, and altitude (for range as the independent variable) - are stored as tabular functions of the chosen independent variable.

Also, it is possible to fly along a nominal path using two approaches:

1). An open-loop approach where the thrust vector is directed over the next period in such a way that by the end of that period, the next reference point is reached.

2). A closed loop approach where the aircraft is continually steered to a continuously commanded trajectory which connects the reference points.

Both of these approaches were examined for simulation of flying the climb profile. The closed loop approach gave superior performance, so only this approach has been retained.

The problem with open loop steering was that it assumed that constant or linearly varying controls would cause the end points of a reference profile to be connected. This assumption did not account for perturbations due to wind, etc. along the way to be taken into account. Although the open loop methods produced paths which had roughly correct values of airspeed and altitude at given range values, these paths had large excursions from the reference flight path angle for the climb profiles.

Another problem with the open-loop approaches was that both α and T were varied to achieve fixed values of V_a and h for given range points. For optimum climb, thrust is usually set at the maximum value. Thus, usually only α remains as a valid control variable.

Another consideration for implementing the climb profile is that there is no reason why a particular cruise condition (altitude, airspeed) has to be achieved when a certain range x is reached. Thus, a more logical independent variable is altitude, with range allowed to be a free variable.

For these reasons, a closed-loop steering approach was devised where reference values of flight path angle (with respect to the air mass) and airspeed are obtained as functions of altitude. (This assumes that altitude is monotonically increasing during climb.) A perturbation control law was set up so that variations in α from a reference value α_o were proportional to variations in γ and V_a from their respective command values.

For dynamic trim, when no wind shear is present, Eqs. (A.5) and (A.9) are

$$\begin{aligned} m\dot{V}_a &= T \cos \alpha - D - W \sin \gamma \;, \\ mV_a\dot{\gamma} &= T \sin \alpha + L - W \cos \gamma = 0. \end{aligned} \tag{A.10}$$

That is, these non-linear equations must be continually solved for T and α to provide a dynamic condition where the specified acceleration $\dot{V}_a$ is achieved for a steady flight path angle γ.

Because γ and V_a tend to change linearly with time, they can be considered as ramp functions. Thus, the closed-loop controller should be considered to be at least a Type 1 system. From Eqs. (A.10), the system perturbation equations are

$$\begin{aligned} m\,\delta\dot{V}_a &= -\,T \sin \alpha\,\delta\alpha - \frac{\partial D}{\partial \alpha}\,\delta\alpha - \frac{\partial D}{\delta V_a}\,\delta V_a - W \cos \gamma\delta\gamma \;, \\ m\,V_a\delta\dot{\gamma} &= T \cos \alpha\,\delta\alpha + \frac{\partial L}{\partial \alpha}\,\delta\alpha + \frac{\partial L}{\partial V_a}\,\delta V_a + W \sin \gamma\delta\gamma \;. \end{aligned} \tag{A.11}$$

The resulting transfer functions between γ, V_a, and α are of the form

$$\frac{\delta\gamma}{\delta\alpha} = \frac{G_B\,(\tau_B\, s + 1)}{(s/\omega)^2 + 2\zeta(s/\omega) + 1}\ , \tag{A.12}$$

$$\frac{\delta V_a}{\delta\alpha} = \frac{G_c\,(\tau_c\, s + 1)}{(s/\omega)^2 + 2\zeta(s/\omega) + 1}\ ,$$

where the time constants, etc. are functions of the parameters in Eq. (A.11).

The control problem can now be interpreted as shown in Fig. A.3. To obtain the Type 1 system, the control law has to be of the form

$$\delta\alpha = (K_1 + \frac{K_2}{s})\ (V_{a_c} - V_a) + (K_3 + \frac{K_4}{s})\ (\gamma_c - \gamma), \tag{A.13}$$

where V_{a_c} and γ_c are the commanded values of V_a and γ. This is the classical proportional-plus-integral controller. Gains are chosen to produce the desired response for removal of profile errors.

For the climb profile, the subroutine STEER1 mechanizes the above approach. To generate the continuous commands V_{a_c} and γ_c, the computations made at each reference point are

$$\frac{\partial\delta}{\partial h} = \frac{\gamma_{n+1} - \gamma_n}{h_{n+1} - h_n}\ , \tag{A.14}$$

$$\frac{\partial V_a}{\partial h} = \frac{V_{a_{n+1}} - V_{a_n}}{h_{n+1} - h_n}\ .$$

Then,

$$\gamma_c = \gamma_n + (h - h_n)\ \frac{\partial\gamma}{\partial h}\ , \tag{A.15}$$

$$V_{a_c} = V_{a_n} + (h - h_n)\ \frac{\partial V_a}{\partial h}\ .$$

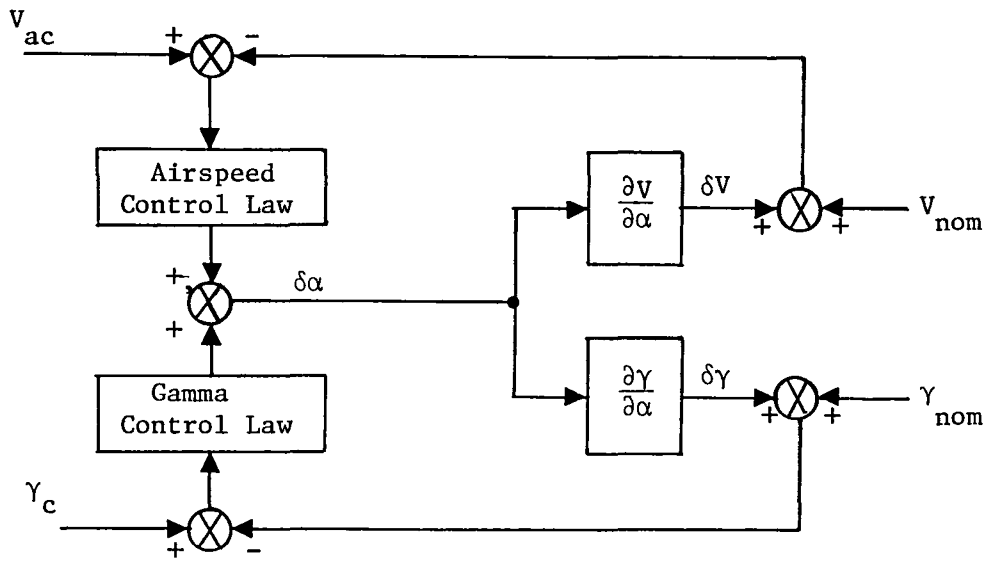

Figure A.3 Control Loops for Perturbation Control of Airspeed and Flight Path Angle.

When the flight path angle is very small (during the initial period of flight and when the aircraft levels off at 10000 ft to gain speed before resuming climb), Eqs. (A.15) do not work well. For these cases, it is more appropriate to set

$$\gamma_c = 0., \tag{A.16}$$

$$V_{a_c} = V_{a_{N+1}} ,$$

and use the control law

$$\delta\alpha = (K_3 + \frac{K_4}{s})(\gamma_c - \gamma) . \tag{A.17}$$

The above method, implemented as STEER1, worked quite well in causing the simulated profile to closely follow the reference path. Only one set of gain values was sufficient for the entire trajectory.

For descending flight, the thrust again is usually constrained (idle) for optimum performance. Also, for this case, the main concern is to reach a fixed altitude when range-to-go to the destination point is a certain value. Thus, above 10000 ft, the airspeed can be allowed to be a free variable. For this case, only inertial flight path γ_{Ic} is required to be controlled.

To generate a continuous command γ_{Ic}, the computation made at each reference point is

$$\gamma_{Ic} = \tan^{-1} \left[(h_{n+1} - h_n) / (x_{n+1} - x_n)\right] . \tag{A.18}$$

Then, the control law is similar to Eq. (A.17), i.e.

$$\delta\alpha = (K_3 + \frac{K_4}{s}) (\gamma_{Ic} - \gamma_I) , \tag{A.19}$$

where inertial values of flight path angle are used rather than those with respect to the air mass. Equations (A.18) and (A.19) form the basis for the subroutine STEER2 which is used for closed-loop control of descending flight. Again, one set of gains is sufficient for the entire descent profile.

Cruise Computations Using the Breguet Equations

A single cruise leg takes place in one vertical plane. Over this leg, it is assumed that the flight path angle is very small and that speed and altitude changes are negligible. Also, for now, it is assumed that there is no wind. With these assumptions specified, the following equations are valid.

$$\begin{aligned} T &= D , \\ L &= W , \\ \dot{x} &= V_a . \end{aligned} \tag{A.20}$$

In addition, the time rate of change in weight can be expressed by the equation

$$\dot{W} = - T\, S_{FC} , \tag{A.21}$$

where S_{FC} is the engine specific fuel consumption.

These equations can be used to formulate the standard range equation as follows:

$$\dot{x} = (dx/dW)\dot{W} = V_a \tag{A.22}$$

Therefore,

$$\begin{aligned} dx/dW &= V_a \frac{1}{\dot{W}} = \frac{-V_a}{T(S_{FC})} \\ &= \frac{-V_a(L/W)}{(T/D)D(S_{FC})} = \frac{-V_a(L/D)}{S_{FC}} \frac{1}{W} \end{aligned} \tag{A.23}$$

The Breguet factor or range factor, R_F, is defined as:

$$R_F \equiv \frac{V_a(L/D)}{S_{FC}} . \tag{A.24}$$

Then,

$$dx/dW = -R_F \frac{1}{W} . \tag{A.25}$$

From Eq. (A.25), one can write

$$x = -\int_{W_{initial}}^{W_{final}} \frac{R_F}{W}\, dW \quad , \tag{A.26}$$

or

$$x = \overline{R}_F \, \ell n \left(\frac{W_{initial}}{W_{final}} \right), \tag*{A(.27)}$$

where $\overline{R}_F$ is the average value of R_F over the range traveled. Using the average value for the range factor $\overline{R}_F$ is an approximation but a very good one for cruise performance. Equation (A.27) is referred to as the range equation.

The range equation is often used to determine an optimum altitude and Mach number to maximize the range.* However, for the purpose of the TRAGEN program, cruise speed, altitude and the required range of the cruise segment are specified, and it remains to find the fuel burn over the cruise segment. Thus the range equation is rewritten as follows:

First, the fuel burned is

$$W_{Fuel} = W_{initial} - W_{final} \quad . \tag{A.28}$$

Then, the range traveled is

$$x = \overline{R}_F \, \ell n \, \frac{1}{1 - W_{fuel}/W_{initial}} \quad . \tag{A.29}$$

Thus, the fuel burned to achieve a given range x is

$$W_{fuel} = W_{initial} \left(1 - 1/e^{(x/\overline{R}_F)} \right). \tag{A.30}$$

---

* Note that this is a relatively trivial optimization result for a commercial transport aircraft since the cost of time is not considered and the climb and descent legs are ignored in the problem.

In TRAGEN, the average Breguet factor $\overline{R}_F$ is computed by evaluating Eq. (A.24) at the initial and final altitude and airspeed conditions specified to be achieved over the given range. Equation (A.30) is used to iterate on the amount of fuel burned over this segment. This is used in turn to compute the final weight to determine the trimmed value of Eq. (A.20) and to obtain the final value of R_F.

APPENDIX B

TRAGEN SUBROUTINE DESCRIPTION

This appendix contains an explanation of the data storage for program OPTIM. Following that is an explanation of the main program, the subroutines, and the functions in alphabetical order.

Data Storage

The major part of the data communications between subroutines in OPTIM is through labelled common statements. There are ten such commons. Their names and a short description of each are:

CCDE	Cruise, climb, descent variables.
CONST	Constants.
CRUISE	Cruise table and associated variables.
DESCRP	Assorted variables.
ERROR	Error traceback information.
GRAPH	Data to be written to Unit 11 and associated variables. Includes the final climb and descent trajectories.
INPUT	All input parameters.
TOA	Time-of-arrival and step climb variables.
TRIJET	Engine data, tri-jet.
TWINJT	Engine data, twin-jet.
WINDP	Wind input data and associated parameters.

As a convenience, the CDC UPDATE capability is used to insert COMMON statements into source decks. This facilitates changing items in COMMON with no loss of program portability, because UPDATE produces a compile file which is directly listable, editable, and compilable by any standard FORTRAN.

Program Explanation

Following is a description of the TRAGEN routines.

MAIN PROGRAM: TRAGEN

The sequence of steps in TRAGEN follows the flow chart presented in Section IV. The purpose of TRAGEN is to simulate an aircraft being commanded to follow a reference profile or to cruise. The profile may either be a climb or a descent as governed by the mission segment flag NSC. It may be either input or computed as governed by the flag ITRAJ.

The program first reads in control flags and other data. This is followed by reading in of variables to initialize the aircraft state. If wind is to be used, it is read in before the initial segment is computed. Likewise, if a reference trajectory is to be read in from Unit 11 it is brought in for the initial segment.

If the segment is an initial climb, or a descent, the control law gains are read in. Then subroutine SETREF is called to set up the reference. CMACTL is then called to integrate the trajectory for comparison with the reference.

If the segment is a climb following some other segment, a step climb to the desired final altitude is inserted first. TRAGEN then continues with the climb and descent logic.

If the segment is a cruise, subroutine ACRUSE is called to control the computation.

After each segment, TRAGEN returns to the beginning to read a new header and new options (as a minimum). It must be ended with a header card followed by an NSC = 5 card.

Subroutines called:	Commons used:
ACRUSE	CCDE
ATLOW	ERROR
CMACTL	INPUT
SETREF	TQHCOM
TRACIT	TRAGEY
TRIM	TVAR
WINDIN	
WINDSH	

ACRUSE

Subroutine ACRUSE prints the initial output for the cruise segment, sets up the initial conditions depending on whether or not this is the initial segment, and calls subroutine CREWZ to perform the cruise computations. If IWIND is not zero, ACRUSE reads in the cruise wind.

Subroutines called:	Commons used:
ATLOW	CCDE
CRUSE	ERROR
FIAS	INPUT
	TRAGEY
	TVAR
	WINDP

ATLOW

This subroutine generates the atmospheric density (in lb sec^2/ft^4), atmospheric pressure (in lb/ft^2), atmospheric temperature (in degrees Kalvin) and speed of sound (in ft/sec) at a given altitude below 20,000 meters (65,617 feet). It also makes the appropriate modifications in atmospheric density and speed-of-sound to account for variations in standard day temperature (represented by the input DTEMP). The 1962 standard atmosphere is used. This version of the program does not calculate a new atmosphere when called at successive times at the same altitude.

CONDATA

This subroutine contains all the data for program constants.

BLOCK DATA - DATTRI

This block data contains the engine data used with the tri-jet aircraft model. Three tables are used to describe idle thrust, idle fuel flow, and maximum continuous engine pressure ratio (EPR).

Subroutines called:	Common used:
None	TRIJET

BLOCK DATA - DATTWN

This block data contains numerical characteristics of the turbofan engine used with the twin-jet aircraft model. Seven tables are used to describe idle thrust and fuel flow for bleed valves open and closed, altitude of surge bleed valve closure, maximum EPR for climb and cruise, and Mach number corrections.

Subroutines called:	Common used:
None	TWINJT

CDRAG

This subroutine calls the appropriate routine to compute the aircraft drag coefficient CD based on the particular aircraft model selected by the input variable IAC. Currently, two models are available, but logic is present to use up to four different aircraft.

Subroutines called:	Commons used:
CDRAG1* CDRAG2 CDRAG3 CDRAG4*	None

* not included with program

CDRAG2

This subroutine computes the drag coefficient CD for some given Mach number EM and lift coefficient CL for a medium range tri-jet transport aircraft model. The value is computed from the coefficients of a polynomial stored in the array COEFF.

Subroutines called:	Commons used:
POLY2	None

CDRAG3

This subroutine computes the drag coefficient CD for some given Mach number EM and lift coefficient CL for a medium range twin jet transport aircraft model. CD is computed by polynomial evaluation, including interpolation of the polynomial and its first derivative in certain regions, as necessary.

Subroutines called:	Commons used:
POLY2	None

CLIFTT

CLIFTT calls the appropriate routine to compute the aircraft lift coefficient for the particular aircraft model selected by the input variable IAC. Currently, two models are available, but logic is present to use up to four different aircraft.

Subroutines called:	Commons used:
CLIFT1*	None
CLIFT2	
CLIFT3	
CLIFT4*	

* not included with program.

CLIFT2

This subroutine computes the lift coefficient CL for a medium range tri-jet transport aircraft as a function of Mach number EM, altitude H, and angle-of-attack ALPHAP. The lift coefficient consists of three terms:

$$C_L = C_L \text{ (basic)} + C_{LO} + C_{L\alpha} \alpha$$

The first term C_L (basic) is a polynomial function of angle-of-attack α. The value of this term is checked against the buffet boundary expressed as a polynomial of Mach number. The second term C_{LO} is a polynomial of Mach number with altitude as the parameter. The third term $C_{L\alpha}$ is also a polynomial of Mach number. The coefficients of the polynomial are fit for different altitudes.

Subroutines called:
POLYE1

Commons used:
None

CLIFT3

This subroutine computes the lift coefficient CL for a medium range twin jet transport aircraft as a function of Mach number EM, altitude H, and angle-of-attack ALPHA. The lift coefficient consists of three terms:

$$C_L = C_L \text{ (basic)} + C_{Lo} + C_{L\alpha} \alpha$$

The first term C_L (basic) is a function of angle-of-attack. The second term C_{Lo} is a function of altitude and Mach number. The third term $C_{L\alpha}$ is also a function of altitude and Mach number. These terms are determined by table lookup.

Subroutines called:
DBLSRC
SERCHI

Commons used:
None

CMACTL

This subroutine computes the actual trajectory for comparison with the reference trajectory. First, CMACTL initializes all variables that are printed out and that are modified by the integration process. At this point, the update process is ready to begin.

The first step of the update (integration) process is writing the simulated, time-varying state variables as determined from integrating the equations of motion. These are followed by a written line of variables obtained from the reference trajectory at about the same point along the profile. The reference trajectory data points are separated by steps in specific energy or altitude of 500 ft.

The next step is to determine whether the end of the integration process has been reached. The subroutine will exit when any of the following take place:

time T $\geq$ TSTOP,

counter ICT > NOPT,

where NOPT is the number of points in the reference trajectory.

Next, the process of generating the steering commands to follow the reference trajectory is simulated. One option (STEER1) is present for climb commands and one (STEER2) is present for descent command generation. These commands consist either of airspeed and/or flight path angle which are used to command continuous changes to angle-of-attack. They also compute how long (DT) these commands hold until the next set of commands should be issued.

Following the issue of the steering commands, the aircraft equations of motion are integrated by calling the integration subroutine GO. Then the counter ICT is updated, certain output variables are computed, and the program loops back to begin the update cycle again.

Subroutines called:	Commons used:
ATLOW	CCDE
GO	ERROR
STEER1	INPUT
STEER2	TQHCOM
	TRAGEN
	TVAR

CREWZ

Subroutine CREWZ calculates the cruise performance of the aircraft when initial and final altitude and speed, initial weight, and desired range are given. An iteration employing Breguet factors is used. Appendix A describes the theory upon which this subroutine is based.

Subroutines called:	Commons used:
ATLOW	CCDE
FIASM	ERROR
PAGE	INPUT
TRIM	TRAGEY
WIND	

DBLSRC

This function performs a double table lookup. Given a function f(x,y), this function interpolates the appropriate arrays to obtain approximate values of f(A,B). The four points which surround (A,B) are first found, and the function is evaluated at each. Then these values are interpolated, first on x and then on y, to obtain the approximate solution.

Subroutines called:	Commons used:
SERCHI	None

ENGEPR

This subroutine calls the appropriate routine to compute the aircraft maximum thrust and EPR, the thrust associated with the input EPR, and the fuel flow rate. The engine model is associated with the particular aircraft model selected by the input variable IAC. Currently, two models are available, but logic is presented to use up to four different aircraft.

Subroutines called:	Commons used:
ENGEP1*	None
ENGEP2	
ENGEP3	
ENGEP4*	

* not included in program

ENGEP2

This subroutine generates the thrust THRUST and the fuel flow rate FDOT for some given altitude H, Mach number EMAKNO and EPR setting. First EPRMX, the maximum continuous EPR, is determined by table look-up for some given temperature Ta and altitude H, where

$$Ta = T(1 + \frac{\gamma-1}{2} (EMAKNO)^2)^2 - 273.15.$$

Here, T is the temperature corresponding to altitude H, after temperature variation correction, and

$\gamma = 1.4$, the ratio of specific heats.

The EPR setting is limited to EPR $\leq$ EPRMX for cruise and EPR $\leq$ EPRMX - .1 for climb or descent.

Second, (FN/δ_e) is computed from a polynomial. Then, the thrust is computed as,

$$THRST = 3(\delta_{am}) (FN/\delta_e).$$

This is the thrust for the medium range tri-jet transport aircraft model. Here, δ_{am} is the pressure ratio

$$\delta_{am} = \frac{P}{P_o} .$$

Here, P is the atmospheric pressure corresponding to altitude H, and P_o is the atmospheric pressure at sea level. A factor of 3 is used since there are three engines.

Finally, the fuel flow rate FDOT is computed as:

$$FDOT = 3 *WFC * \delta a *Kc$$

where

$$Kc = .00\ 223181\ Ta + .9675897,$$

$$\delta a = \delta_{am} (1 + \frac{\gamma-1}{2} (EMAKNO)^2)^{\gamma/\gamma-1} .$$

Also, WFC is the fuel-flow rate computed as a polynomial of EPR, where the coefficients of the polynomial depend on both altitude and Mach number.

Subroutines called:

ATLOW
DBLSRC
POLYE1

Commons used:

CCDE
ERROR
INPUT
TRIJET

ENGEP3

This subroutine generates the thrust THRUST and the fuel flow rate FDOT for some given altitude H, Mach number EM and EPR setting. First EPRMX, the maximum continuous EPR, is determined by table look-up, (Tables 6 and 7 in Block Data) for some given temperature Ta and altitude H, where

$$Ta = T(1 + \frac{\gamma-1}{2} (EM)^2) - 273.15.$$

Here, T is the temperature corresponding to altitude H, after temperature variation correction, and

$$\gamma = 1.4, \text{ the ratio of specific heats.}$$

The EPR setting is limited to EPR $\leq$ EPRMC.

Second, (FN/δ_e) is computed from a polynomial. Then, the thrust is computed as,

$$THRST = 2(\delta_{am}) (FN/\delta_e) ,$$

where δ_{am} is the pressure ratio

$$\delta_{am} = \frac{P}{P_o} .$$

Here, P is the atmospheric pressure corresponding to altitude H, and P_o is the atmospheric pressure at sea level. A factor of 2 is used since there are two engines.

Finally, the fuel flow rate FDOT is computed. A polynomial is used to calculate WFC for a given EPR and altitude. At values of EPR < 1.6, there is also a correction for Mach number (Table 10 in Block Data). Then:

$$FDOT = 2 *WFC * \delta a *Kc ,$$

where

$$K_c = .0022\ T_a + 0.97 ,$$

$$\delta a = \delta_{am} (1 + \frac{\gamma-1}{2} (EM)^2)^{\gamma/\gamma-1} .$$

Subroutines called:	Commons used:
DBLSRC	CCDE
POLY2	ERROR
SGLSRC	INPUT
	TWINJT

ENGIDL

ENGIDL is called during descent to compute thrust and fuel flow rate for idle EPR. It does this through table look-up for the appropriate aircraft.

Subroutines called:	Commons used:
DBLSRC	ERROR
SGLSRC	TRIJET
	TWINJT

FIAS

FIAS returns Mach number as a function of indicated airspeed (in feet per second) and atmospheric pressure.

Subroutines called:	Commons used:
None	None

FIASM

FIASM returns indicated airspeed in knots as a function of Mach number and atmospheric pressure.

Subroutines called:	Commons used:
None	CONST

FSUB

This subroutine computes the derivatives for the integration process. It is called four times per integration step by the integration subroutine GO. The following steps are taken to compute the derivatives:

1. The flight path angle with respect to the air mass is computed as

$$\gamma = \sin^{-1} \dot{h}/V \quad .$$

2. The Mach number and atmospheric density are computed by calling ATLOW.

3. The longitudinal wind magnitude and its gradient with respect to altitude are computed by calling WIND1.

4. The control variables are computed based on the steering option used. They are for ICNFL:

1: STEER1 option. Here, airspeed and flight-path-angle commands are computed as linear functions of altitude:

$$V_c = V_{c1} + h \frac{\partial V}{\partial h} ,$$

$$\gamma_c = \gamma_{c1} + h \frac{\partial \gamma}{\partial h} .$$

Then, the actual values are subtracted from these commands to generate $\delta\gamma$ and δV errors. A proportional plus integral control law of the form

$$\delta\alpha = K_1 \delta V + K_2 \int \delta V + K_3 \delta\gamma + K_4 \int \delta\gamma,$$

is used to compute continuous perturbations to the steady value of angle-of-attack. Angle-of-attack is limited between $(-4^o, + 22^o)$. Thrust is set at a maximum value. During the level parts of the climb ($\gamma \leq 0.1^o$), only the flight path errors ($\delta\gamma, \int \delta\gamma$) are used in the control law. Each segment of this option is usually cut off on time. However, during level acceleration, the segment is cut when airspeed reaches the next reference value.

2: STEER2 option. Here, a constant inertial flight path angle (GMC) is commanded. The actual value is estimated and subtracted, and a proportional plus integral control law is used to compute perturbations to the angle-of-attack command:

$$\delta\alpha = K_3\,\delta\gamma + K_f \int \delta\gamma.$$

Again, total angle-of-attack is limited to $(-4^{\circ}, +22^{\circ})$. The thrust is set at idle value by setting EPR to 1.1.

5. Lift, drag, and mass of the aircraft are computed.

6. Thrust and fuel flow rate are computed.

7. The five basic derivatives representing the longitudinal dynamics of the aircraft are computed:

$$\ddot{h} = (L \cos \gamma - W + T \sin (\gamma+\alpha) - D \sin \gamma)/m,$$

$$\dot{V} = (T \cos \alpha - D - W \sin \gamma)/m - \frac{\partial V_w}{\partial h} V \sin \gamma \cos \gamma \cos \delta,$$

$$\dot{x} = V_g$$

$$\dot{h} = \dot{h},$$

$$\dot{W} = -\dot{f}/3600.$$

Subroutines called:	Commons used:
ATLOW	CCDE
CDRAG	ERROR
CLIFTT	INPUT
ENGEPR	TRAGEY
ENGIDL	TQHCOM
WIND	WINDP
WIND1	

GO

This subroutine is a Runge-Kutta-Gill fourth order numerical integration package which integrates a set of eight first order ordinary differential equations. The step size of the independent variable is H. X and XF are the initial and final values of the independent variable (which is time, for this application).

Subroutines called:	Commons used:
FSUB	ERROR
OSUB	TQHCOM

OSUB

This subroutine has two purposes: (1) to write out intermediate values of system variables at the end of each integration step, and (2) to stop integration along a certain segment. For ICNFL:

:1 STEER1 option. For climbing flight ($\gamma > 0.1^{o}$; ICFL = 1), the segment is cut off (XF = XDQ(1)) when altitude H reaches the next reference value HP. For near level flight ($\gamma \leq 0.1^{o}$; ICFL = 2), the segment is cut off when airspeed VA reaches the next reference value VC1.

:2 STEER2 option. For descending flight, the segment is cut off when the range value X becomes greater than the next reference value RP.

Subroutines called:	Commons used:
NONE	INPUT
	TRAGEY
	TQHCOM

PAGE

This subroutine advances the printout to the top of the next page.

POLYE1

This function evaluates the polynomial

$$Y = b(1) + b(2)\ X + b(3)x^2 = \ldots b(M)X^{m-1}$$

POLY2

POLY2 evaluates the polynomial

$$\begin{aligned} Z = {} & c_{11} + c_{12}x_2 + \ldots\ c_{1m}x_2^{n-1} \\ & + c_{21}x_1 + c_{22}x_1x_2 + \ldots\ c_{2n}x_1x_2^{n-1} \\ & + \ldots \\ & + c_{m1}x_1^{m-1} + c_{m2}x_1^{m-1}x_2 + \ldots + c_{mn}x_1^{m-1}x_2^{n-1} \end{aligned}$$

REFCOM

This subroutine computes a reference flight profile that is similar to one that would be specified in a pilot's handbook for a particular aircraft. (For example, aircraft are usually limited to be under 250 kt IAS below 10000 ft. The tri-jet might have a climb schedule of 320 kt IAS/0.73M and a descent schedule of 0.73M/320 kt IAS.) Thus, this subroutine computes a climb profile that follows the following sequence:

1. Accelerate from V0 to VIAP1 (indicated airspeed in kt) at altitude H0.
2. Climb to 10000 ft at VIAP1 in 500 ft steps.
3. Accelerate from VIAP1 to VIAP2 (indicated airspeed in kt) at 10000 ft.
4. Climb to intersection with Mach number RM3 at indicated airspeed VIAP2, in 500 ft steps.
5. Climb to altitude HF at Mach number RM3, in 500 ft steps.

At each step, the variables time (T1), range (R1), altitude (H1), true airspeed (VT1), flight path angle (GAM1), specific energy (E1), fuel burned (F1), power (EPR) setting (EP1), and windspeed are computed and stored in the array A.

If the path is a climb profile, maximum EPR is used. For descent, EPR is set to 1.1 and idle thrust and fuel flow rates are used.

REFCOM calls the subroutine VTCM to convert indicated airspeed or Mach to True airspeed and to obtain thrust, energy, energy rate and other variables at a particular altitude. Then the computation sequence is

$$\Delta E = E - E_p$$

$$\Delta t = E/\dot{E}$$

$$\gamma = \sin^{-1}((\Delta h/\Delta t)/V_{T_p})$$

$$\Delta R = (V_T + V_{T_p})\ \Delta t/2$$

$$W = W_p - \dot{W}_p \Delta t$$

where the subscript p indicates the value of a variable at the previous altitude.

Subroutines called:	Commons used:
VTCM	CCDE
WIND	ERROR
	INPUT
	TRAGEY
	TVAR
	WINDP

SERCHI

The array TX(·) is monotonically increasing. This subroutine searches the index ℓ such that

$$TX_\ell \leq x \leq TX_{\ell+1} ,$$

and returns both ℓ and pf where

$$pf = \frac{x - TX_\ell}{TX_{\ell+1} - TX_\ell} .$$

SETREF

This subroutine sets up the reference trajectory, either by reading it in or by calling REFCOM to compute it. If input parameter ITRAJ = 1, the data input procedure is set to accept output from the companion program OPTIM. For a climb profile, this comes in the form:

CGRAF(I,J) for I = 1, JCLIMB and J = 1,10.

JCLIMB is the number of data points. There are up to 10 variables for each point. For the descent profile, the input data come in the form:

DGRAF(I,J) for I = 1, JDESCN and J = 1,10.

JDESCN is the number of data points, and again, there are up to 10 variables for each point. Because OPTIM generates the descent profile backwards in time, the DGRAF array variables are reordered with time and range given negative values, and fuel burned is manipulated to be subtracted from the initial weight rather than added to the final weight.

If ITRAJ = 2, SETREF sets up the input and calls the subroutine REFCOM to compute the reference profile. This may either be a climb or descent profile as governed by the flag NSC.

Subroutines called:	Commons used:
PAGE	ERROR
REFCOM	INPUT
	TRAGEY
	IVAR

SGLSRC

This function evaluates a single function F at the point A. This is done by linear interpolation to obtain A's location in the array X and using the tabulated values of F(X).

Subroutines called:	Commons used:
SERCHI	None

STEER1

This subroutine provides air-referenced flight-path-angle and airspeed commands that are used in FSUB for closed-loop steering during climbing flight. This routine is based on the assumption that thrust is set to maximum value and that angle-of-attack perturbation commands can be related to the difference between actual and commanded values of airspeed and flight path angle. The flight path and airspeed commands are generated as functions of altitude from values (γ_+, V_+, h_+, γ_n, V_n, h_n) taken from the reference trajectory:

$$\frac{\partial \gamma}{\partial h} = \frac{\gamma_+ - \gamma_n}{h_+ - h_n} \; .$$

$$\frac{\partial V}{\partial h} = \frac{V_+ - V_n}{h_+ - h_n} \; ,$$

$$\gamma_{c1} = \gamma_n - h_n \frac{\partial \gamma}{\partial h} \; ,$$

$$V_{c1} = V_n - h_n \frac{\partial V}{\partial h} \; .$$

$$V_c = V_{c1} + h \frac{\partial V}{\partial h}$$

$$\Delta t = 2(h_+ - h)/(V_+ \sin \gamma_+ + V_c \sin \gamma)$$

When the next reference value of flight path angle (γ_+) is less than 0.1°, the above equations are replaced with

$$\gamma_{c1} = 0$$

$$V_{c1} = V_+ \; .$$

Subroutines called:	Commons used:
NONE	TVAR

STEER2

This subroutine provides inertial flight-path-angle commands that are used in FSUB for closed-loop steering during descending flight. This routine is based on the assumption that thrust is set to idle value and that angle-of-attack perturbation commands can be related to the difference between actual and commanded values of flight path angle. The flight path angle commands are generated by keeping altitude as a fixed function of range-to-go to the landing point. Values of altitude (h_+) and range-to-go (r_+) are taken from the next reference point. Then

$$\frac{\partial h}{\partial X} = \frac{h_+ - h}{r_+ - X},$$

$$\gamma_c = \tan^{-1}\left(\frac{\partial h}{\partial X}\right).$$

This value of flight path angle command is stopped when the next reference value of range-to-go (r_+) is reached.

Subroutines called:	Commons used:
NONE	TVAR

TRACIT

In case of error, this subroutine provides a "walk back" through the subroutine calling hierarchy. If the subroutine is set up to recognize the computation or logic to be in error, then TRACIT can be used to find the source of the error.

TRIM

This subroutine is used to compute the trim conditions for medium range transport aircraft. This subroutine computes angle-of-attack α and thrust T to keep the aircraft in trim for constant speed level flight, for a given altitude and for a given Mach number.

With γ the flight path angle, the equations of motion in the horizontal and vertical directions are as follows:

$$\frac{W}{g}(dv/dt) = T \cos \alpha - D - W \sin \gamma$$

$$\frac{W}{g} v(d\gamma/dt) = T \sin \alpha + L - W \cos \gamma$$

For a trimmed condition:

$$(dv/dt) = (d\gamma/dt) = 0.$$

The two equations are combined to eliminate thrust to give the equation:

$$(W\cos\gamma - L)\cos\alpha - (D\sin\alpha + W\sin\gamma)\sin\alpha = 0.$$

This equation is solved by iterating with angle-of-attack, α.

Once the aircraft is trimmed, the thrust is solved from the drag by

$$T = (D + W\sin\gamma)/\cos\alpha \ .$$

This required thrust is matched by iterating on values of power setting (EPR) and calling subroutine ENGEPR. Once the correct power setting is determined, the engine fuel flow is also known.

Subroutines called:	Commons used:
CDRAG	CCDE
CLIFTT	DESCRP
ENGEPR	ERROR
	INPUT

VTCM

This subroutine computes true airspeed, energy, energy rate, thrust, drag, lift, and fuel rate from indicated airspeed, altitude, and weight. The computation sequence is as follows:

Pressure	$p = f(h)$
Temperature	$T = f(h)$
Density	$\rho = p/(3092.4\ T)$
Speed of sound	$a = 65.76\ \sqrt{T}$
Mach number	$M = (5.(((((V_{IAS}/2496.5)^2 + 1.)^{3.5} - 1.)(2116.22/p) + 1.)^{2/7} - 1.))^{1/2}$
True airspeed	$V_T = M\ a$

If M is given, then

Indicated airspeed	$V_{IAS} = 2496.5((((p/2116.22)((1. + .2M^2)^{3.5} - 1.) + 1.)^{2/7} - 1.))^{1/2}$
Specific energy	$E = h + V_T^2\ /2.g$
Thrust	$Th = f(h,M,EPR)$
Fuel flow rate	$\dot{w} = f(Th,h,M)$
Lift	$L \cong W$
C_L	$C_L = L/(\rho V_T^2\ S/2)$
C_D	$C_D = f(C_L,M)$
Drag	$D = \rho V_T^2\ S\ C_D/2$
Energy rate	$\dot{E} = (Th - D)V_T/W$

Subroutines called:

ATLOW FIAS
CDRAG FIASM
ENGEPR
ENGIDL

Commons used:

CCDE
ERROR
INPUT

WINDIN

This subroutine reads in the wind profile (the magnitude and direction of wind as a function of altitude). The wind magnitude input is in knots and the program converts it to ft/sec and stores it in the VW array. The wind direction is stored in PSIW in degrees. The input represents the direction the wind is coming from. The program adds 180° to this value to obtain the vector direction. The altitudes corresponding to these wind magnitudes and directions are stored in array HWIND. The wind may be input as a single profile, valid over the entire flight, or as separate climb, cruise and descent profiles. In the case of a step climb, the cruise profile is used for lower cruise, step climb, and upper cruise segments.

Subroutines called:	Commons used:
None	INPUT WINDP

WINDSH

This subroutine uses the input profile of wind magnitude VW( ) and direction PSIW( ) to compute north and east components of wind shear as a function of altitude HWIND( ). These shear components change every 2000 ft of altitude.

Subroutines called:	Commons used:
NONE	INPUT WINDP

WIND

This subroutine computes the wind velocity as a function of altitude. This is combined with the aircraft velocity with respect to the air mass to compute ground velocity. Inputs to this program are H, the altitude in feet; PSIG, the aircraft heading in degrees; VTAS, the aircraft air speed; GAMMR, the angle of attack; VW, and PSIW arrays. The outputs from this program are VWA, the wind speed, and VG, the aircraft ground speed.

Subroutines called:	Commons used:
SERCHI	DESCRP
	ERROR
	INPUT
	WINDP

WIND1

This subroutine computes the gradient of the wind speed in the north and east directions from the input array WINCP( ) and the altitude. These values are then used to compute the gradient of wind DWDH with respect to altitude along the longitudinal axis of the aircraft. The wind magnitude is also computed.

Subroutines called:	Commons used:
	INPUT
SERCHI	WINDP

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Program User's Guide

16 Abstract

This document is a technical description and a user's guide for a computer program -- called TRAGEN -- which is used to simulate an aircraft steered to follow a climbing, cruise, or descending profile or any sequential combination of these flight phases. Specifically, the program simulates the longitudinal dynamics of a medium range twin-jet or tri-jet transport aircraft. For the climbing trajectory, the thrust is constrained to maximum value, and for descent, the thrust is set at idle. For cruise, the aircraft is held in the trim condition. For climb or descent, the aircraft is steered to follow either (a) a fixed profile which is input to the program or (b) a profile computed at the beginning of that segment of the run. For climb, the aircraft is steered to maintain the given airspeed as a function of altitude. For descent, the aircraft is steered to maintain the given altitude as a function of range-to-go. In both cases, the control variable is angle-of-attack. The given output trajectory is presented and compared with the input trajectory. Step climb is treated just as climb. For cruise, the Breguet equations are used to compute the fuel burned to achieve a given range and to connect given initial and final values of altitude and Mach number.

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